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What do cyclists need to see to avoid single-bicycle crashes?

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The number of single-bicycle crash victims is substantial in countries with high levels of cycling. To study the role of visual characteristics of the infrastructure, such as pavement markings, in single-bicycle crashes, a study in two steps was conducted. In Study 1, a questionnaire study was conducted among bicycle crash victims ($n = 734$). Logistic regression was used to study the relationship between the crashes and age, light condition, alcohol use, gaze direction and familiarity with the crash scene. In Study 2, the image degrading and edge detection method (IDED-method) was used to investigate the visual characteristics of 21 of the crash scenes. The results of the studies indicate that crashes, in which the cyclist collided with a bollard or road narrowing or rode off the road, were related to the visual characteristics of bicycle facilities. Edge markings, especially in curves of bicycle tracks, and improved conspicuity of bollards are recommended.

Statement of Relevance: Elevated single-bicycle crash numbers are common in countries with high levels of cycling. No research has been conducted on what cyclists need to see to avoid this type of crash. The IDED-method to investigate crash scenes is new and proves to be a powerful tool to quantify 'visual accessibility'.

Keywords: visual accessibility; perception; bicycle facilities; cyclist safety; single-bicycle crashes

1. Introduction

Many studies have been conducted on how drivers' visual capabilities and limitations can be supported by road design. Marked centre and edge lines provide a visual reference to guide motorists in the driving task (McGee and Hanscom 2006). The Norwegian *Handbook on Road Safety* (TOI 1997) provides a comprehensive summary of crash studies. These studies date back several decades, showing the long research history into safety and visibility of infrastructure for drivers of motorised vehicles. As a consequence, most countries have strict guidelines for markings on roads for drivers. In contrast, no edge-of-track markings are recommended for guidance of cyclists in manuals for bicycle facilities (Director of Environmental Services 1998, Jensen *et al*. 2000, CROW 2006). This suggests an untested general assumption that cyclists can do without enhanced visual contrast for environmental elements within the riding distance due to a lower speed than drivers. The majority of the research on cyclist safety is performed from the perspective of car drivers. Previous research mainly focused on the visibility of cyclists and pedestrians to avoid collisions with motorised vehicles (i.e. cyclists should be visible for motorists), for instance, Kwan and Mapstone (2004) on visibility aids, Jensen (2007) and Nygårdhs *et al*. (2010) on the visibility of bicycle crossings at intersections.

This paper questions the assumption that cyclists can do without a minimal level of guidance and conspicuity of (design-related) obstacles on their way. The absence of a minimal level of contrast may lead to single-bicycle crashes (only one cyclist involved), where riders lose their lane position or collide with obstacles as was suggested by den Brinker *et al*. (2007). This issue is of importance as the number of single-bicycle crash victims in the Netherlands is substantial and continues to rise. Each year, Accident and Emergency Departments treat 46,000 injuries sustained in single-bicycle crashes. Of these, approximately 6000 victims are admitted to the hospital, one-third of all traffic victims. A high number of single-bicycle crashes and substantial medical costs are common in countries with a high proportion of cyclists (Elvik and Mysen 1999, Veisten *et al*. 2007, Ormel *et al*. 2008). Single-bicycle crashes are very rarely reported in official road crash statistics (Nordentoft *et al*. 1989, Elvik and Mysen 1999). The dearth of data might explain why few studies have been conducted in this area, and even fewer that focus on single-bicycle crashes in relation to road characteristics (Kortstra and Schoone-Harmsen 1987, Nyberg *et al*. 1996, Schoon and Blokpoel 2000).

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The study by Kortstra and Schoone-Harmsen (1987) was based on victims' statements at Emergency Care Departments, of which one-third was detailed enough to be included in the analysis. Schoon and Blokpoel (2000) used a survey of bicycle crash victims who were treated at an Emergency Care Department in 1995. The answers to open-ended questions were coded if the victim was involved in a single-bicycle crash. The study by Nyberg *et al.* (1996) is the most relevant one for the present study, as it is the only one that specifically focused on the relationship between single-bicycle crashes and road characteristics. They performed a questionnaire study among bicyclists treated as inpatients and outpatients at the University Hospital of Northern Sweden. Only crashes of victims who deemed the road or bicycle track surface to be the major contributing factor to the crash were studied. The road surface factors that had contributed to the injuries included snow, ice, wet leaves and gravel on the roadway, cracks, holes, uneven paving and a steep lateral slant. Victims also collided with kerbs and stationary objects. Inspections of the scene were not conducted; therefore, it was not possible to measure the visual characteristics of the infrastructure.

Owing to the fact that this study focuses on the role of the characteristics of the visual design in single-bicycle crashes, i.e. guidance and conspicuity of obstacles, the present study was conducted in two steps. In the first step, a survey was performed among single-bicycle crash victims to investigate whether crash characteristics could be related to vision (see Study 1 in section 3). In the second step, crash scenes were inspected and an objective psychophysical method was used to measure its visual characteristics (see Study 2 in section 4).

2. Cyclists' needs for markings and other visual cues

Cyclists' needs for markings and other visual properties of the infrastructure, i.e. 'visual accessibility', should be based on the tasks they perform and the effort required to carry out these tasks. Theory on focal vs. ambient vision that is fruitfully studied in the context of the driving task (paragraph 2.1) is used in order to develop a framework of reference with this heuristic for the cycling task (paragraph 2.2).

2.1. Focal vs. ambient vision

Focal and ambient visual resources vary along a number of dimensions (Leibowitz and Post 1982, Previc 1998). The primary functions of the focal visual system are visual search, object recognition and related tasks requiring high visual acuity. According to Previc (1998), this system relies on saccades as the primary motor system. Although focal vision can extend beyond the fovea, its strengths are greatest in the fovea. In contrast, the ambient visual system is involved in orienting in earth-fixed space, spatial orientation and postural control in locomotion. This system typically encompasses the front 180° of the visual field, is lower field dominant (because of the importance of optic flow information in ground-based locomotion) and involves peripheral vision.

Schieber *et al.* (2008) have adapted Donges' (1978) two-level model of driver steering that is in accordance with the ambient-focal dichotomy:

(1) The guidance-level that involves focal/far vision to garner information from the 'far' road ahead. The driver uses this information to anticipate and prepare for hazards and future alterations in the course of the road.
(2) The stabilisation-level that involves ambient/near vision regarding current (i.e. instantaneous) deviations between the vehicle's actual path and its desired path. Peripheral vision is used to track and minimise instantaneous errors in lane position.

Schieber *et al.* (2008) refer to an experiment that indicates where ambient/near visual processes give way to focal/far visual processes. In an experiment in a driving simulator it was tested how far down the roadway, defined from the position of the driver, edge lines needed to be visible to support optimal lane tracking. Lateral lane position variability reached minimum levels within just 2 s of roadway preview time (COST 331 1999). The stabilisation-level seems insufficient for lane-keeping on a road with tight curves. Drivers with a simulated low visual acuity have some deficiencies in terms of preparatory vehicular positioning in anticipation of sharp curves, resulting in more lane excursions (Brooks *et al.* 2005).

Schieber *et al.* (2008) as well as Horrey *et al.* (2006) have summarised results of research on the driving task, which can be interpreted in terms of the focal-ambient dichotomy. Vehicular guidance (i.e. ambient vision) is found to be remarkably robust in the face of great reductions in available high-spatial-frequency information, achieved experimentally via blur and low luminance. Conversely, driving processes thought to be mediated by focal vision, i.e. sign and hazard recognition at a distance, are increasingly worsened due to low visual acuity (e.g. Higgins *et al.* 1998, Owens and Tyrrell 1999, Brooks *et al.* 2005). Leibowitz and Post (1982) formulated the 'selective degradation hypothesis' to describe the fact that visual recognition abilities are selectively degraded in low illumination while visual guidance is preserved. The results of experiments using the forced-peripheral driving technique are in line with the ambient-focal heuristic. Drivers are able to perform a lane-keeping task relying exclusively on peripheral vision (Summala *et al.* 1996), while they do not perform well in detecting a closing headway or looming vehicle in peripheral vision (Summala *et al.* 1998, Terry *et al.* 2008).

Drivers of all ages experience serious visual impairment in low illumination conditions, particularly a degradation of visual recognition abilities, i.e. the 'selective degradation hypothesis' (Owens and Andre 1996). Older drivers also suffer from a deterioration of steering performance in low light conditions (Owens and Tyrrell 1999, Wood and Owens 2005). This problem may be related to a gradual decline of peripheral vision, contrast sensitivity, dark adaptation and glare sensitivity across the adult lifespan (Johnson and Keltner 1983, Owens and Andre 1996, Jackson *et al.* 1999). Younger drivers are overconfident at night because visual guidance is preserved. Consequently, they generally stay unaware of their reduced recognition abilities. The fact that older drivers do experience decreased steering performance may explain their reluctance to drive at night (Owens and Tyrrell 1999).

2.2. Comparison between cycling and driving

Cycling is compared with driving and the ambient-focal dichotomy is used to hypothesise about visual requirements for cycling facilities. The first question is about the requirements for ambient vision. Cyclists are in the open while drivers are in their car; thus, cyclists' lower visual field is less restricted, which offers them more optic flow, i.e. more support for ambient vision. This eases the cycling task, but, in contrast to driving, cycling requires stabilising the bike. Although cyclists have a low speed compared to drivers, they cannot completely rely on focal vision to carry out their task. For instance, while steering through a gap between two obstacles, it is difficult to control the path of the bike by fixating on the obstacles. Moreover, a decrease of cycling speed causes an increase of the effort required to stabilise the bicycle. Under unfavourable circumstances (e.g. gusty headwinds) cycling may require a track width of up to 80 cm (CROW 2006).

Because of their lower speed, cyclists need a smaller 'visibility distance' than drivers to support ambient vision. Even in this smaller distance, peripheral information needs to be available. Pedestrians, who even have a lower speed, are already known to suffer from a restricted peripheral vision, so cyclists are supposed to suffer from that too. A loss in the peripheral visual field (i.e. an extreme degradation of ambient vision) is associated with unwanted contacts and disorientation (Turano *et al.* 2002). Likewise, Lemmink *et al.* (2005) found that turning time during a shuttle run test (i.e. running back and forth between two parallel lines) increases significantly when sprinting with a restricted peripheral field of view, indicating the use of peripheral vision for the control of directional changes.

The second question for the comparison between driving and cycling is about the requirements for focal vision. Drivers generally drive faster than cyclists and are likely to confine their gaze to a narrower view. The faster a vehicle moves, the further the driver needs to look ahead for hazards and changes in the course of the road. In straight-road driving, gaze is increasingly constrained by increasing speed (Rogers *et al.* 2005). In contrast, as cyclists travel at a lower speed, they would not have to look as far ahead, i.e. cyclists need a smaller visibility distance. However, problems may arise when important information is poorly visible in the visual periphery within this distance. First, focal vision may deteriorate if the minimal requirements of short-range visibility for ambient vision are not met. More fixations on the roads' edges would be needed to determine the course of the road if the edges are poorly visible. This would worsen focal vision as it relies on saccades. Second, even if the requirements for ambient vision are met, cyclists need to focus their attention on other traffic in complex traffic situations or may look at the surroundings. Visibility in the visual periphery is needed to guarantee that a bollard (post used to keep motor vehicles off a cycle track), road narrowing or curve timely captures the attention of approaching cyclists.

Peripheral visual information is generally believed to help select the object to which the eyes are sent next (Loschky *et al.* 2005). Detection is dependent on the size and salience of objects. Saliency typically arises from contrasts between items and their neighbourhood (den Brinker and Beek 1996, Schubö 2009). Background 'clutter' (i.e. high information density) decreases the visibility of critical information (Hole *et al.* 1996). In the case of cyclists, it should be borne in mind that there is often salient information for drivers in their surroundings. The standards for markings and street lighting for roads are at a higher level than for bicycle facilities. A change in the course of an unmarked bicycle track along a well-marked, well-lighted and wide road may go undetected, even if a cyclist would fixate on the right part of the bicycle path. Habak *et al.* (2002) found that strong signals from the periphery facilitate the percept when central signals are weaker, but not the reverse. The comparison herein between driving and cycling suggests that critical information needs to be visible in the visual periphery for safe cycling.

2.3. Research approach

As single-bicycle crashes are rarely recorded by the police, a questionnaire study was conducted (i.e. Study 1) among single-bicycle crash victims treated at Accident and Emergency Departments to be able to study the crash characteristics. Part of the questions in the inquiry are likely to be related to the impact of the visual characteristics of the infrastructure: light conditions; age; influence of alcohol; familiarity with the crash scene (i.e. with obstacles and sudden changes in the course of the road); gaze direction. Study 2 is added to strengthen the basis for conclusions by investigating the visibility (in the visual periphery) of critical information at crash scenes. A visual analysis was conducted based on pictures that were taken under the same light and viewing conditions as prior to the crash.

3. Study 1: Questionnaire sent to bicycle crash victims

3.1. Procedure and method

Consument en Veiligheid (Consumer Safety Institute) performed a retrospective study. Questionnaires were sent to cyclists who had had a crash with their bicycle and were treated at an Emergency Care Department. These victims were retrieved from Letsel Informatie Systeem (Dutch Injury Surveillance System), which records statistics of people being treated at the Emergency Care Departments of 13 hospitals in the Netherlands, following an accident, violence or self-inflicted injury. The selection of hospitals is a representative sample of hospitals in the Netherlands with a continuously staffed Emergency Care Department.

The outcomes of the previous studies on single-bicycle crashes that were mentioned in section 1 were used to develop a questionnaire consisting of closed and open-ended questions. The open-ended questions and an example of a closed question are included in Table 1. Other questions were about the location, the date and time when the crash occurred, the purpose of the trip, the speed at the time of the crash, the light and weather conditions at the time of the crash, use of alcohol, drugs and medicine prior to the crash, potentially distracting activities at the time of the crash (e.g. mobile phone use or conversing with a fellow cyclist), gaze direction prior to the crash, the type of and quality of the bike, injuries, average bicycle use before the crash and changes in behaviour afterwards. It took about 20 min to answer all the questions. The survey was sent 2 months after the victim was treated at the Emergency Care Department.

Table 1. Two examples of questions in the survey*.

Examples of questions
No. 1. Description of the crash. We would like to know what happened precisely when you had the crash.
1a. On what kind of road were you riding? What was the purpose of your trip? Was there an extraordinary situation?
1b. What happened next, what went wrong?
1c. Where you injured? What injury did you sustain? Which area(s) of your body was wounded?
No. 4. What happened exactly (you can mark more than one category)? I fell:
• While mounting the bike
• While dismounting from the bike
• While braking
• While descending a slope
• While climbing a slope
• While overtaking
• While turning left
• While turning right
• While I was just cycling (no specific manoeuvre or activity)
• Other . . .
I collided with an object or obstacle:
• Lighting post
• Traffic sign
• Bollard
• Fence or wall
• Kerb
• Tree
• Animal
• Other . . .

*The original Dutch questionnaire is included in Appendix 1 in the report on single-bicycle crashes (Ormel et al. 2008). Available online from: http://www.fietsberaad.nl/library/repository/bestanden/Onderzoek_Enkelvoudige_fietsongevallen.pdf

Between February and June 2008, 2975 questionnaires were sent; 1156 (39%) were returned. Such response was comparable to similar surveys, such as other surveys by the Dutch Consumer and Safety Institute. A total of 1142 could be used for analyses. Of these victims, 16% were hospitalised after treatment at the Emergency Care Department. Unanswered questions were treated as missing values in the analysis.

As the assumption that cyclists can do without a minimal level of guidance and conspicuity of (design-related) obstacles on their way is questioned in section 1, single-bicycle crashes were categorised into a group that may be related to the visual design of the crash location (group V) and a group that contains all other crashes (group NV). Crashes were classified to group V if the critical information that the cyclist needed to see to be able to avoid the crash was intentionally designed, i.e. the edge of the road, the obstacle or the tram rails. Crashes unrelated to vision were classified to group NV, for instance, losing balance due to baggage that becomes entangled in the spokes of a wheel, or due to cracks and holes in the road surface (i.e. road factors that were not part of the initial design). This resulted in the following two categories:

(1) Group V (n = 180): cyclist collided with a kerb, bollard or road narrowing, fell onto the shoulder (or crashed into an off-road object), or fell because a wheel was deflected on contact with tram rails parallel to the direction of bicycle traffic.
(2) Group NV (n = 554): skidding, loss of control due to bumps and holes in the road surface, a bicycle defect, loss of control while mounting or dismounting the bicycle, etc.

Binary logistic regression was used to assess the association of crashes in group V with the following variables: gender; age (under or above 60 years of age); light condition at the time of the crash; alcohol use; gaze direction at the time of the crash (behind, to something next to the road, or else). Gender was included as a control variable. In this paper, the age group of above 60 years of age is referred to as 'older cyclists'. The victims in group NV were used as controls. Odds ratios with 95% CI and p values were calculated.

An additional analysis was added to provide insight in the avoidance of adverse light conditions by older cyclists. To determine the number of kilometres travelled by bicyclists the Dutch Mobility Study (Mobiliteits Onderzoek Nederland) was used. This is a survey on the travel behaviour of the Dutch population (SWOV 2009). Data were used from the period of 2003–2007, February–June, i.e. the months in which the crashes happened. Times of departure were combined with the Dutch sunrise and sunset timetable (KNMI 2009), to separate between kilometres travelled in daylight and in twilight and darkness. The proportion of kilometres travelled by bicycle in darkness and twilight was determined per age group.

3.2. Results

There were 734 single-bicycle crashes, of which 180 were classified as visual-design related (group V) and 554 that were classified in the other group (group NV). The results of the binary logistic regression indicate that the crashes in group V are related to age, alcohol use and the gaze direction before the crash (see Table 2). The crashes also tended to happen more often in dark and twilight and to cyclists who were unfamiliar with the crash location, but these differences are not significant.

In Figure 1, the percentage of kilometres travelled by cyclists in darkness and twilight is presented by age.

Table 2. Association of single-bicycle crashes with visually related variables.

	Accidents*			
	Group V (n = 180)	Group NV (n = 554)	OR (95% CI)†	p
Gender:				
Male	94 (52)	295 (53)	0.96 (0.67–1.38)	0.843
Female	86 (48)	258 (47)	1.00 (reference)	–
Age (years):				
≥60	70 (39)	166 (30)	1.71 (1.17–2.50)	<0.01
<60	110 (61)	387 (70)	1.00 (reference)	–
Light condition:				
Dark and twilight	46 (26)	84 (15)	1.60 (0.92–2.77)	0.095
Daylight	133 (74)	467 (85)	1.00 (reference)	–
Alcohol use‡:				
Yes	31 (17)	43 (8)	2.20 (1.14–4.25)	0.019
No	148 (83)	510 (92)	1.00 (reference)	–
Gaze direction before the accident:				
At something next to the road	18 (10)	15 (3)	4.21 (1.99–8.93	<0.001
Behind	14 (8)	14 (3)	3.87 (1.76–8.54)	<0.001
Other direction	147 (82)	524 (95)	1.00 (reference)	–
Familiarity with the accident location:				
Not familiar	32 (18)	76 (14)	1.45 (0.90–2.33)	0.128
Familiar	144 (82)	470 (86)	1.00 (reference)	

Group V = single-bicycle crashes that may be related to the visual design of the crash location; Group NV = all other crashes.
*Number and column percentages (in parentheses); discrepancies in totals are due to missing covariate values.
†Odds ratios (OR) (group V vs. group NV) and 95% CI from binary logistic regression analysis.
‡Two or more alcohol-containing beverages, 6 h before the accident.

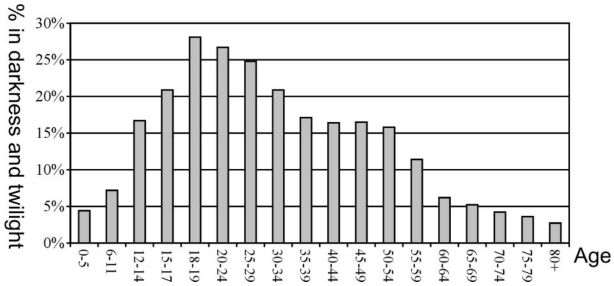

Figure 1. Share of the distance travelled by bicycle in darkness and twilight per age group.

Almost 10% of all bicycle kilometres are travelled in darkness and twilight. As indicated in Figure 1, older cyclists avoid riding their bicycle in darkness. This finding may explain why light condition is not significantly related to crashes in group V. The cyclists with the worst visual capabilities may avoid adverse light conditions.

Group V is divided into the following two categories to conduct additional analyses on gaze direction and familiarity with the crash scene:

(1) Cyclist collides with a bollard or road narrowing or rides off the road in a curve (n = 83).
(2) Cyclist hits a kerb, rides into a shoulder or falls because a wheel is deflected on contact with tram rails on a straight road section or crossing (n = 97).

Collisions in the first group happen more often to distracted cyclists (see Table 3) and cyclists who were unfamiliar with the crash location (see Table 4). As Table 5 indicates, crashes in the second group happen more often among cyclists who looked behind prior to their crash.

The questionnaire also included a question about physical problems. In total, 10 victims responded that they had problems with their vision (1.4% of all victims of single-bicycle crashes). According to Melief and Gorter (1998), 1–2% of the Dutch population is visually impaired. There are no data on their use of bicycles. According to den Brinker *et al.* (2007), some people who are blind, according to the definition (visual acuity of 3/60 or less in the better eye or restriction of visual field to 10°), are still using their bicycle. In fact, for people who do not have a driving licence due to a visual acuity below 30/60, it can be the only efficient means of independent transport. The number of victims is too small to draw firm conclusions, but the results are in line with expectations. As indicated in Table 6, visually impaired cyclists are more frequently involved in the crashes of group V.

Table 3. Crash types of cyclists distracted by objects or the scenery next to the road.

Single-bicycle accident type	Cyclist looked next to the road			Row
Cyclist:	Yes	No	Total*	(Yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	4	92	96	4%
(2) collides with bollard or rides off the road in a bend	14	69	83	17%
(3) other	15	539	554	3%
Total	33	700	733	5%

*The second category is higher than the first and third (χ^2(2, n = 733) = 33.7; $p < 0.001$).

Table 4. Familiarity of single-bicycle crash victims with the accident location.

Single-bicycle accident type	Victim familiar with the accident location			Row
Cyclist:	Yes	No	Total*	(Yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	84	11	95	12%
(2) collides with bollard or rides off the road in a bend	60	21	81	26%
(3) other	470	77	547	14%
Total	614	109	723	15%

*The second category is higher than the first and third (χ^2(2, n = 723) = 8.8; $p = 0.012$).

Table 5. Crash types of cyclists who looked behind prior to the accident.

Single-bicycle crash type	Cyclist looked behind			Row
Cyclist:	Yes	No	Total*	(Yes)
(1) hits a kerb or rides into a shoulder, or falls because a wheel is deflected on contact with tram rails (straight section or crossing)	11	85	96	11%
(2) collides with bollard or rides off the road in a bend	3	80	83	4%
(3) other	14	540	554	3%
Total	28	705	733	4%

*The first category is higher than the second and third (χ^2(2, n = 733) = 17.8; $p < 0.001$).

Table 6. Single-bicycle crashes among visually impaired victims.

Visually impaired	Crashes			Row (group V)
	Group V[†]	Group NV	Total*	
Yes	6	4	10	60%
No	173	549	722	24%
Total	179	553	732	24%

Group V = single-bicycle crashes that may be related to the visual design of the crash location; Group NV = all other crashes.
*Visually impaired cyclists are more often involved in crashes in group V ($\chi^2(1, n = 732) = 6.9$; $p < 0.01$).
[†]Collision with kerb, bollard or road narrowing, fall onto the shoulder, wheel deflected on contact with tram rails.

4. Study 2: Image degrading and edge detection analyses of single-bicycle crash locations

4.1. Procedure and method

A psychophysical analysis was performed to determine the visibility of large shapes (e.g. the distinction between the verge and the road surface) in the visual periphery: the image degrading and edge detection-method (IDED-method). The IDED-method was developed to determine the visibility of contrasts in the periphery of normally sighted people and the overall visibility of contrasts for people with low vision (den Brinker and Daffertshofer 2005). The basic principles of the method are that the contrast-transfer properties of the eye's optical system are known to be nearly as good in the periphery as in the fovea (Wang *et al.* 1997) in contrast to the visual acuity that very rapidly falls off with eccentricity (Larson and Loschky 2009). Therefore, the visibility of an object at a certain eccentricity is determined by the visual acuity associated with the eccentricity and a minimum (constant) contrast. Visual acuity is determined by image degrading (i.e. the first step of the IDED-method); contrast level by edge detection (i.e. the second step of the IDED-method). The IDED-method was applied on all crash scenes of which photographs could be taken under the same light and weather conditions as during the crash.

About half of the respondents who filled in the questionnaire reported their telephone number or email address. Victims of crashes in group V were interviewed. It was possible to exactly locate 37 crash scenes. Of these 37, 16 were excluded because the interview revealed that it was unlikely that the characteristics of the visual design played a role in the crash. For instance, one of the victims hit a bollard that was occluded by a fellow cyclist just in front of her. All the 21 remaining crash scenes were inspected and analysed with the IDED-method.

Photographs were taken under the same conditions as during the crash: light, twilight or dark and wet or dry road-surface. The distance ahead of the crash location was 12.5 m, based on the following reasoning. According to Schieber *et al.* (2008), drivers need about 2 s of preview time to support ambient/near vision. Rumar and Marsh (1998) have summarised literature on preview times and concluded that 5 s is a realistic preview time for long-range visual guidance, with 3 s as an absolute minimum. Cyclists have an average speed of around 15 km/h, or 4.2 m/s (CROW 2006). These data suggest a visibility distance of 12.5 m for focal/far and ambient/near vision, within which the roads' edges and (gaps between) obstacles need to be visible in the visual periphery.

In the first step of the analysis, the images are degraded to simulate the effect of a given lowered acuity that is typical for a certain level of eccentricity. Technically, a Gaussian low pass filter degrades the image (Roelofs 1997). The second step uses edge detection, according to Sobel, that is calibrated to display all the contrasts that exceed a critical contrast level as measured according to Michelson. The contour lines in the resulting image show details that are visible given the predefined visual acuity and contrast level. Although 0.3 is often advised as a minimum contrast level for the design of the build environment (Wijk 2008), a lower level of 0.15 was used, as ambient vision is known to be especially sensitive to low-contrast/low-spatial-frequency information in normally sighted adult observers (Schieber *et al.* 2008). An iterative process is used to calculate at which level of visual acuity and associated eccentricity the critical information is visible. Information that the cyclist needed to see to be able to avoid the crash is labelled as 'critical', i.e. the edge of the road surface, the obstacle or the tram rails.

Figure 2a,b presents an example of the result of an IDED-analysis of a location where a bicycle path is delineated with a clear edge-of-track marking. Figure 2b shows that the edge line remains visible when the picture is blurred to a level of acuity of 0.1, the highest level of blurring that was tested. The relationship between the level of blur and the level of visual acuity was applied, as determined by Roelofs (1997), who used Landolt ring targets. A visual acuity of 0.1 corresponds to an eccentricity of 20°. For the relationship with eccentricity, research by Larson and Loschky (2009), who examined the limits of visual resolution in natural scene viewing, was used.

4.2. Results

4.2.1. The IDED-method

The 21 crash scenes were divided into three categories:

- cyclist hits a kerb or rides into a shoulder (n = 10);

- cyclist collides with a bollard or road narrowing (n = 7);
- cyclist falls as a wheel was deflected on contact with tram rails (n = 4).

The results of the IDED-analyses for these three categories are shown in Table 7. The average maximum acuity to which the pictures could be blurred without losing the critical information is shown in the right column. The critical information remains visible at an average level of acuity of 0.27 for the first, 0.18 for the second, and 0.12 for the third category, corresponding to eccentricities of 8, 12, and 15 degrees. The estimation for the last category is likely to be an underestimation, as two of the pictures were not blurred further than the maximum level we tested.

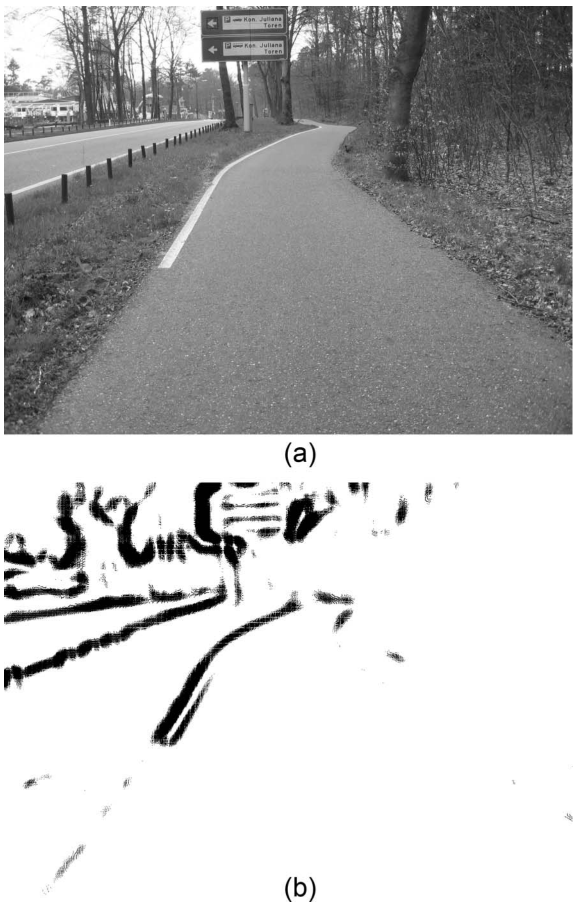

Figure 2. (a) Cycle path delineated with a clear edge-of track marking; (b) result of the image degrading and edge detection analysis of the photograph in Figure 2a that is blurred to a level of acuity of 0.1 (only contrast differences above 0.15 are shown).

Figures 3a,b and 4a,b present the IDED-analyses of two situations in the first category. Figure 3a shows the situation where, even without blur, no luminance differences could be found between the verge and the road surface. This implies that the road edge was difficult to see, even when looked at under a high level of acuity (the dashed line shows the left side of the bicycle track). Figure 4a shows a curve where the contrast between the cycle path and the sidewalk was minimal. The spaces between the tiles offered sufficient contrast to be visible, but only at a relatively high level of acuity. An arrow that suggested a straight continuation of the path remained visible when the picture was blurred to a level of acuity of 0.1.

Figure 5a,b shows the results of an IDED analysis of a crash scene where the victim hit a bollard in the middle of the cycle track. The bollard remains visible when blurred to a level of visual acuity of 0.2. However, an additional difficulty is that the bollard is masked in that it is coloured red–white and placed in the middle of a reddish-coloured bicycle path with a dashed white centreline. Figure 6a,b shows the results of an IDED analysis of a crash scene where the victim fell because a wheel was deflected on contact with rails parallel to the direction of the bicycle traffic. The tram rails remain visible at the highest level of blurring due to the light that is reflected by the tram rails.

Given the results of the IDED analyses and the descriptions of the crashes by the victims, it seems that some crashes were predominantly caused by deficiencies of focal vision, while others were primarily caused by problems with ambient vision. For instance, the victim did not notice the presence of a curve in the

Table 7. Information on the crash scenes and results of the IDED analyses.

Type of crash scene	Light condition: Dark or twilight	Light condition: Day light	Road situation: Curve or intersection	Road situation: Straight section	Examples in Figures	Average level of acuity (minimum – maximum)*
Cyclist hits a kerb or rides into a shoulder	6	4	8	2	3a,b; 4a,b	0.27 (1–0.013)
Cyclist collides with a bollard or road narrowing	3	4	3	4	5a,b	0.18 (0.27–0.13)
Wheel was deflected on contact with tram rails	3	1	2	2	6a,b	0.12 (0.35–0.10)
Total	13	8	13	8		

IDED = image degrading and edge detection.
*Acuity corresponding to the level of blur to which the critical information remained visible.

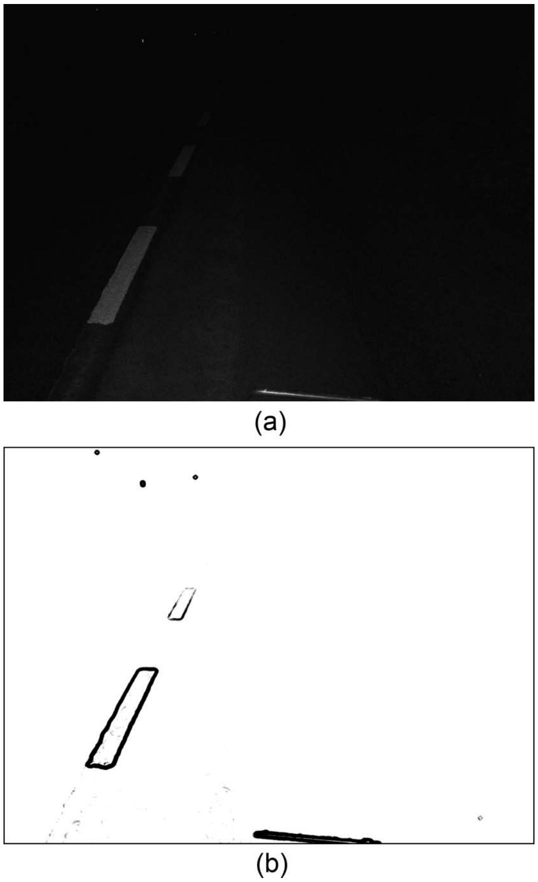

Figure 3. (a) Single-bicycle crash scene where the victim road into the verge; (b) result of the image degrading and edge detection (IDED) analysis of the photograph in Figure 3a that is not blurred (the luminance difference of the road's edge is too low to be detected by the IDED-method, even without blurring).

bicycle track at the crash scene that is presented in Figure 4a. As he did not notice the presence of the curve, it is likely that the crash was predominantly related to problems with focal vision. Conversely, the victim who rode off the road at the scene presented in Figure 3a was riding along a straight bicycle lane, as was clearly indicated by the dashed line along the left side (the line remained visible if the picture was blurred in an extra analysis to a low level of acuity of 0.1). She stated that she noticed too late that she rode off the road and then skidded. It is likely that problems with ambient vision, i.e. monitoring the bike's path, contributed to her crash.

4.3. Additional measurement: the detection conspicuity of obstacles

An additional psychophysical method, 'the detection conspicuity measure' (Toet *et al*. 1998), was conducted to determine the conspicuity of the obstacles in the

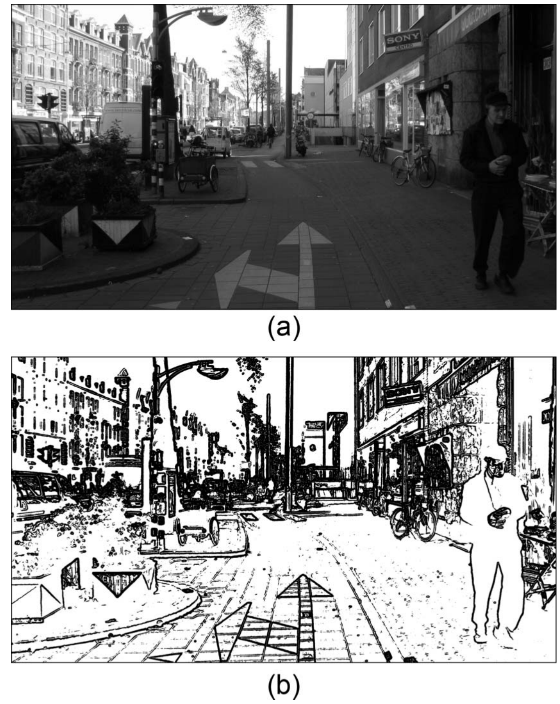

Figure 4. (a) Single-bicycle crash scene where the victim hit a 3 cm high kerb; (b) result of the image degrading and edge detection analysis of the photograph in Figure 4a that is blurred to a level of acuity of 0.5 (only contrast differences above 0.15 are shown).

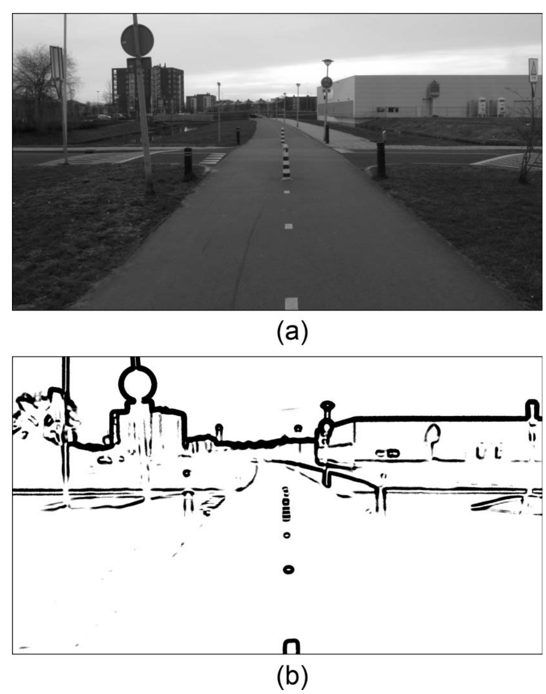

Figure 5. (a) Single-bicycle crash scene where the victim hit a bollard; (b) result of the image degrading and edge detection analysis of the photograph in Figure 5a that is blurred to a level of 0.2 (only contrast differences above 0.15 are shown).

Figure 6. (a) Single-bicycle crash scene where the victim fell because the front wheel was deflected on contact with tram rails; (b) result of the image degrading and edge detection analysis of the photograph in Figure 6a that is blurred to a level of 0.1 (only contrast differences above 0.15 are shown).

second category in section 4.2. As this method is designed for small targets in terms of viewing angle, it is not appropriate for judging the other two categories in section 4.2. In this approach, detection conspicuity is operationally defined as the maximal lateral distance between target and eye fixation at which the target can be distinguished. Toet *et al.* (1998) found a correlation of 0.84 ($n = 62$) between detection conspicuity as determined by their method and search time.

The detection conspicuity of seven obstacles (six bollards and one road narrowing) was determined by the above described conspicuity measure. The angular distance between the fixation location at which the obstacle was first noticed and the obstacle was, on average, 13° with a minimum of 6 and a maximum of 22°. The average level of eccentricity found with the conspicuity measures matched the average level of eccentricity of 12° that was found using the IDED-method. Moreover, a Pearson correlation of 0.77 ($n = 7$; $p = 0.043$) was found between the results of the conspicuity measures and the IDED-analyses.

5. Discussion

While past research (e.g. Nyberg *et al.* 1996) demonstrated the relevance of road surface factors such as ice on the roadway and uneven paving for single-bicycle crashes, the present study has focused on the indirect factor of visibility of bicycle facilities and obstacles. It was hypothesised that the following categories of single-bicycle crashes are visual-design related: cyclist collides with a kerb, bollard or road narrowing; falls onto the shoulder (or crashed into an off-road object); or falls because a wheel is deflected on contact with tram rails parallel to the direction of the bicycle traffic. Study 1 revealed that several visually related factors were indeed correlated with these crashes, which supports the hypothesis. Compared to other victims, victims of these crashes more often used alcohol prior to the crash and were more often over 60 years of age (i.e. with lower visual capabilities).

The crashes tended to happen more often under adverse light conditions although that difference was not significant. The fact that older cyclists avoid cycling under adverse light conditions may explain this finding. In other studies, it was found that older drivers limit their exposure to driving situations that they believe to be more difficult (e.g. rain, night, heavy traffic, rush hour) (Ball *et al.* 1998). This has been linked to the fact that older drivers, in contrast to younger drivers, experience decreased steering performance under low luminance conditions (Owens and Tyrrell 1999). Older cyclists' reluctance to cycle at night may be related to the same problem in addition to other factors such as feelings of insecurity. This might indicate that they suffer from a similar impairment of ambient vision that is needed for precise steering.

To further establish the relationship with the characteristics of the visual design, 21 crash locations were investigated in Study 2. The IDED analyses revealed that the critical information was difficult to see in the visual periphery at crash scenes where the victim rode off the road or collided with a bollard or road narrowing. The present results indicate that visibility of critical information in the visual periphery is indeed important for safe cycling. The IDED analyses revealed fewer problems with regard to the visibility of tram rails. It is likely that these crashes are primarily caused by other factors.

For Study 2, 37 scenes of crashes in group V were exactly located. Of these 37, 16 were excluded because the additional interview revealed that it was unlikely that the characteristics of the visual design played a role in the crash (e.g. a bollard was occluded by a fellow cyclist). Suppose the researchers had the same detailed crash information in Study 1 as was available for the small sample of crashes in Study 2. In that case, they could have classified more precisely between crashes that are related or unrelated to the visual design, resulting in reduced noise in the dependent variable that was used and probably in stronger results than were already found in Study 1. For instance, of the crashes in group V, about one-quarter happened in darkness or twilight, while more than half of the crashes that were selected for the IDED analyses happened in adverse light conditions.

5.1. *Ambient and focal vision*

Detailed information of the 21 crashes in Study 2 indicated that problems with both ambient and focal vision played a role in the investigated crashes. Study 1 revealed differences between crashes within group V that may be related to the distinction between ambient and focal vision. This first group, crashes in which a cyclist hit a kerb or rode into a shoulder on a straight section, happened more often to cyclists looking behind, but not more often to cyclists looking at something at the side of the road (compared with victims of other single-bicycle crashes). As there was no specific danger to be identified, focal vision seems less relevant. Ambient vision is likely to be more important as looking behind limits peripheral vision and requires balance. The second group, crashes in which a cyclist hit an obstacle or rode off the road in a curve, happened more often to cyclists looking at something at the side of the road, but not more often to cyclists looking behind (i.e. the other way around). Recognising the danger, i.e. focal vision, seems more important in these crashes. Viewing at larger eccentricities hinders focal vision.

Although answers on gazing patterns may be biased, as victims might be motivated to describe their crashes in ways that place blame externally, such a bias cannot completely explain the difference in gaze direction that was found between the two crash groups within group V. Moreover, crashes in the second group happened more often to cyclists, who were unfamiliar with the crash location, i.e. had fewer expectations to guide visual search, because one does not know where to expect hazards (Martens and Fox 2007). This result suggests that the focal operations that are typically well represented in consciousness play a more important role in crashes involving a curve or obstacle than ambient functions, which often operate in the absence of awareness (Leibowitz and Post 1982).

5.2. *Recommendations for practitioners*

The present authors recommend starting where single-bicycle crashes are concentrated and no side effects for motorists are to be expected, i.e. obstacles and curves in cycle tracks. This can be realised by applying edge lines on curves in bicycle paths, especially paths with high levels of cycling, no street lighting or a risk of glare from oncoming vehicles. Two-way cycle tracks can be treated with warning centrelines in curves (long-stretched lines instead of short lines) as is advised in the Dutch Design manual for bicycle traffic (CROW 2006). The present authors recommend increasing the conspicuity of bollards by colours that contrast well with their surroundings and by the use of an introductory profiled marking that also alerts cyclists riding behind another cyclist. It should also be assessed whether a bollard is necessary to keep drivers off a cycle track, based on its attractiveness for motorists and the possible harm caused by illegal use.

This study shows that characteristics of the visual design play a role in crashes where cyclists collide with a kerb, bollard or road narrowing, or ride onto the verge, but it does not indicate what the minimal requirements for visibility are. It is too early to advise edge-lines on all bicycle facilities. For instance, before deciding to install edge lines on cycle lanes, road authorities should take possible side effects into account, such as an increase of drivers' speed (Steyvers and de Waard 2000).

Apart from measures to limit the risk of cyclists riding off the road, measures can be taken to limit the consequences when cyclists fail to keep the bike in the centre of the lane. Bicycle facilities can be designed sufficiently wide and with a small difference in height between the surface of the road and the verge to enable cyclists to return to the road safely.

5.3. *Recommendations for future research*

The IDED-method was used to determine the visibility of obstacles and large shapes in the visual periphery for normally sighted people. For obstacles (i.e. small targets in terms of viewing angle), the results of the IDED analyses were compared with the results of the detection conspicuity measure in section 4.3. The results of both measures matched fairly well, which was an important validation step of the IDED-method. Nonetheless, further research is desirable. First, the validation with the detection conspicuity measure was done with normally sighted observers and should be extended to other groups, as cycling facilities should be designed to meet the needs of the large majority of cyclists, including older and low vision cyclists (i.e. 'Design for All'). Second, the IDED-method was validated only with relatively small obstacles, i.e. six bollards and one road narrowing. However, cyclists discern the course of the road by large shapes with rather low contrasts, such as the separation between the road surface and the verge. Research on the usability of information for cyclists should focus on the ability to resolve the location and orientation of large shapes in relation to their contrast and eccentricity. The detection conspicuity measure is not suitable as a validation procedure for large shapes that cover a larger area of the visual field.

The results of this study indicate that characteristics of the visual design of bicycle facilities play a role in certain single-bicycle crashes. However, the question of what the minimal requirements are to meet the needs of the large majority of cyclists is still open. In 2010, the Dutch Ministry of Transport, Public Works, and Water Management issued an experimental study to investigate the minimal contrasts needed for safe cycling. This study will focus on the effect of different contrasts on cycling performance in both photopic and scotopic conditions and with young, older and low vision cyclists. This will generate knowledge for guidelines and for architects to design solutions that are both attractive and sufficient to meet the needs of cyclists, including low vision people.

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